Investigating the spectral nature of soiling and its impact on multi-junction CPV systems

Eduardo F. Fernández and Florencia Almonacid
University of Jaen, Spain

Leonardo Micheli
National Renewable Energy Laboratory (NREL), USA

Greg P. Smestad
Sol Ideas Technology Development, USA

Matthew Muller
Leidos, USA

Universidad de Jaén

CEAEMA
CENTRO DE ESTUDIOS AVANZADOS EN ENERGÍA Y MEDIO AMBIENTE

14th International Conference on Concentrator Photovoltaics (CPV-14)
Puertollano, Spain
April 16-18 2018

CONTENT

- Motivation
- Previous results: unified global investigation
- Impact on multi-junction CPV systems
- Preliminary conclusions

Motivation

Accumulation of dust, dirt and particles on the surface of PV modules and/or lenses of CPV systems

Drop in power output: up to 70%.

Drop in energy yield: 0 to 6% in the U.S./EU

Non-uniform soiling: mismatch between units or sub-modules

The **International PV Quality Assurance Task Force** (PVQAT, "PV cat") leads global efforts to craft quality and reliability standards. Website: http://www.pvqat.org (*Task group 12*) PVQAT International Force

Soiled Residential PV System of David Bernal in Los Angeles (Photo by Greg Smestad)

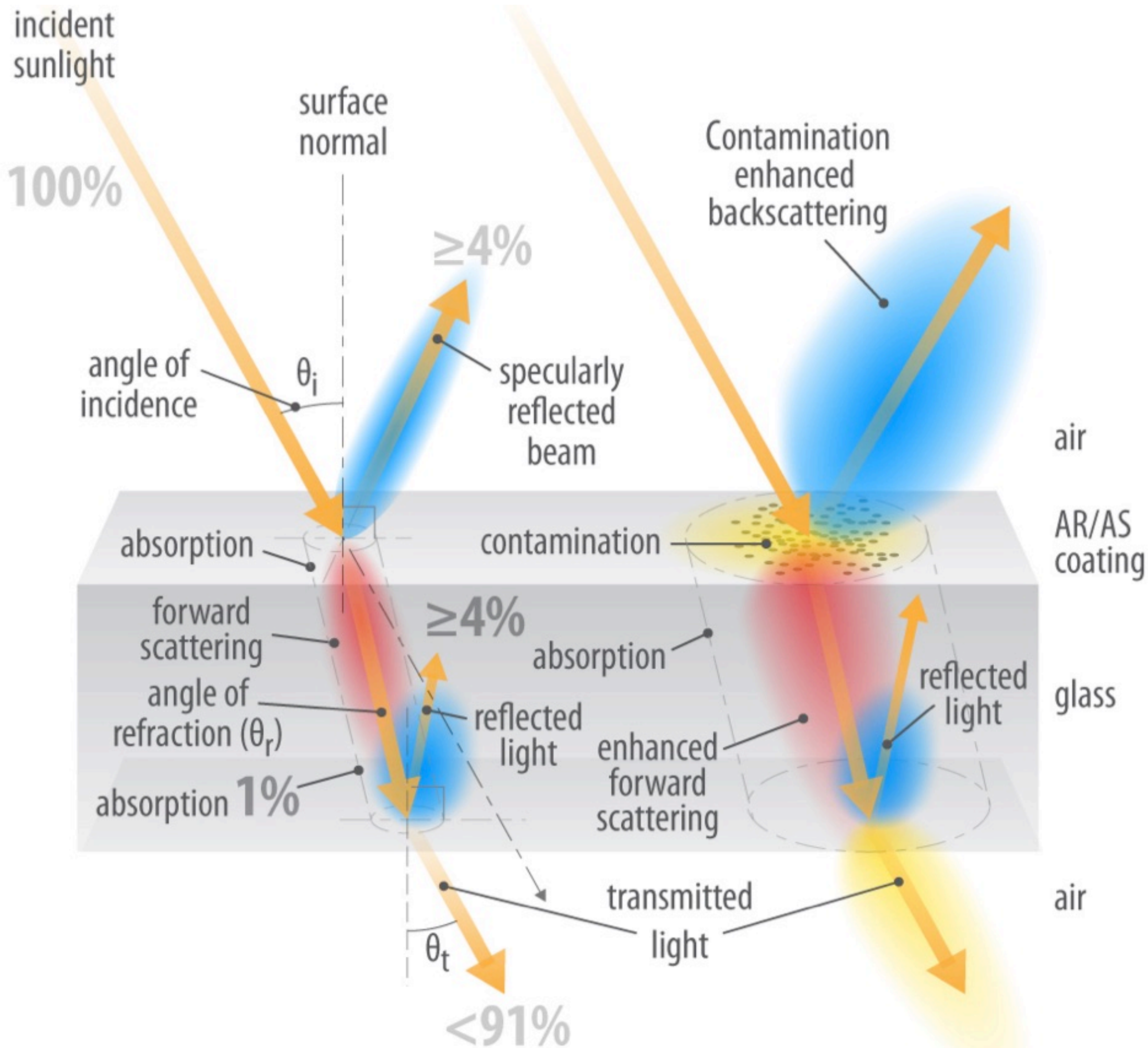


Diagram Courtesy of Al Hicks, NREL

Definition of Particulate Matter

Particulate matter (PM): concentration (*μg/m³*) of solid particles and liquid droplets suspended in 1 m³ of air.

ø < 10 um

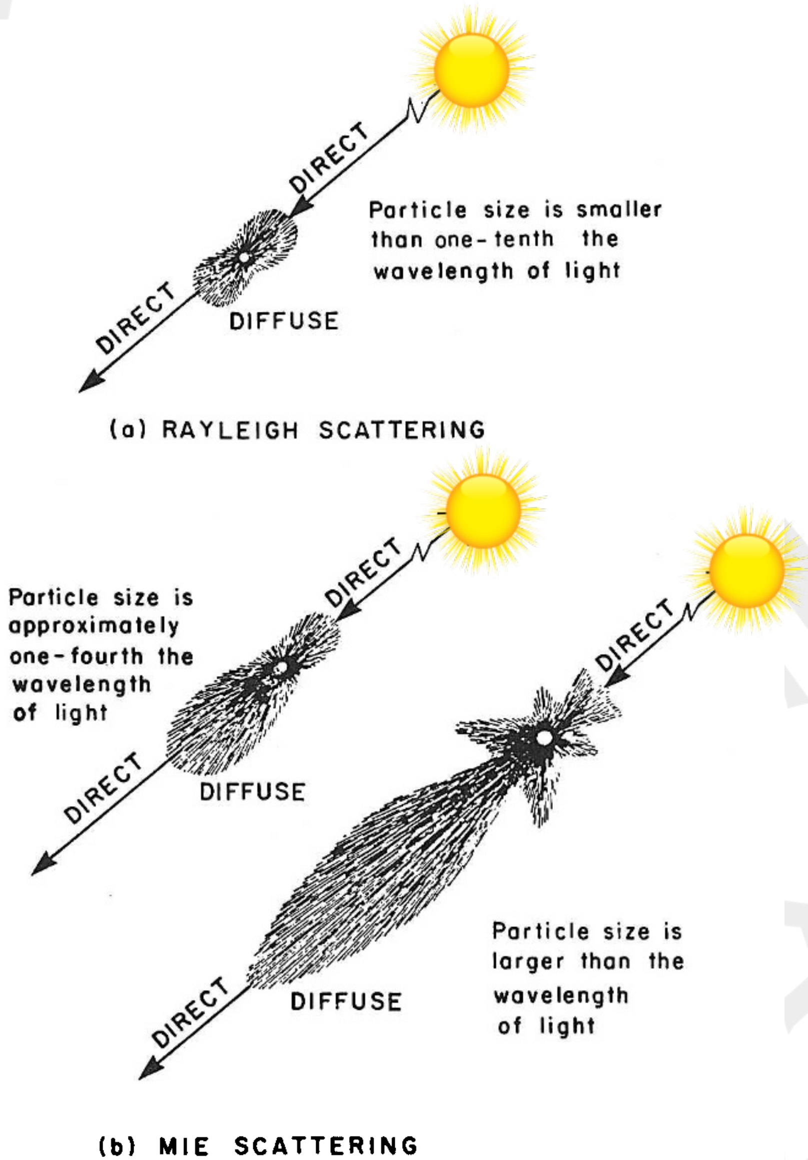
PM_{10} Sources:

Crushing or grinding operations
Dust stirred up by vehicles on roads

ø < 2.5 um

$PM_{2.5}$ Sources:
Motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, industrial processes.

Source: https://www.airnow.gov/index.cfm?action=aqibasics.particle



Atmospheric Scattering

- Decrease of the optical transmittance
- Modification of the spectral content of irradiance
- Impact on the angular distribution of irradiance

An Introduction to Solar Radiation, Muhammad Iqbal, Academic Press, New York, 1983, Chapter 6.

Previous studies

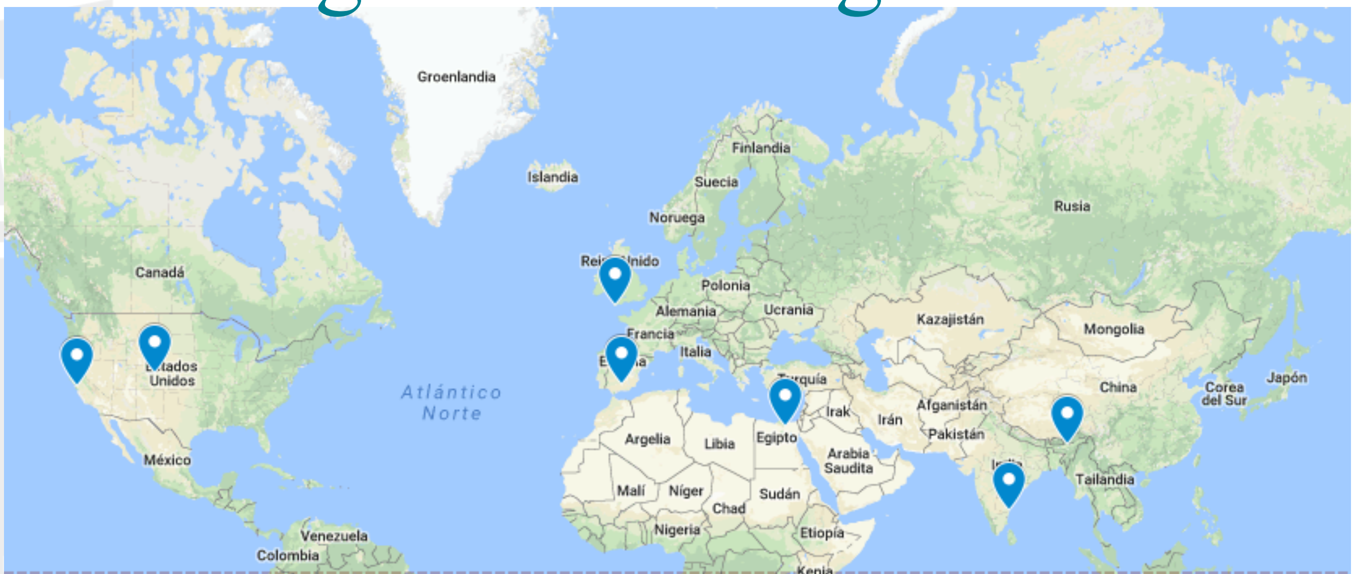
- G. Calvo-Parra, María Martínez, D. Sánchez, Óscar de la Rubia and Pierre Chatenay, "Soiling effects comparison between CPV plants in continental and desert climates", AIP Conference Proceedings, 2017, 1881, 020005.

- A. Sayyah, et al, "Mitigation of soiling losses in concentrating solar collectors," 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, 2013, pp. 0480-0485.

- W. Anana et al., "Soiling impact on energy generation of high concentration Photovoltaic power plant in Morocco," 2016 International Renewable and Sustainable Energy Conference (IRSEC), Marrakech, 2016, pp. 234-238, doi: 10.1109/IRSEC.2016.7983994.

- P. D. Burton and B. H. King, "Spectral Sensitivity of Simulated Photovoltaic Module Soiling for a Variety of Synthesized Soil Types," in IEEE Journal of Photovoltaics, vol. 4, no. 3, pp. 890-898, May 2014, doi: 10.1109/JPHOTOV.2014.2301895.

Unified global investigation

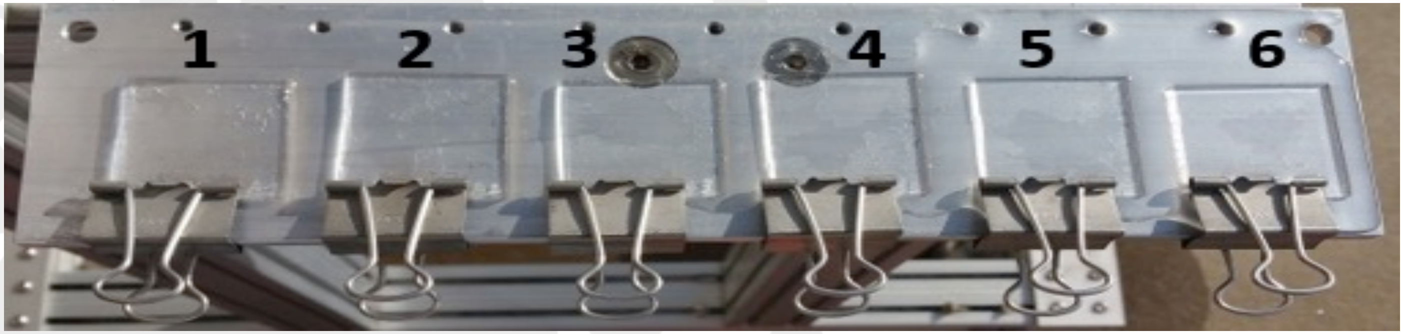


City, Country	*Coordinates*	*Climate classification*
Chennai, India	13.08, 80.27	Equatorial savannah with dry winter (Aw)
El Shorouk City, Egypt	30.12, 31.61	Desert climate (Bwh)
Golden (CO), USA	39.74, -105.18	Snow climate, fully humid (Dfb)
Jaén, Spain	37.79, -3.78	Warm temperate climate with dry summer (Csa)
Penryn, UK	50.17,-5.13	Warm temperate climate, fully humid (Cfb)
San José (CA), USA	37.29, -121.91	Warm temperate climate with dry summer (Csb)
Tezpur, India	26.70, 92.83	Warm temperate climate with dry winter (Cwa)

L. Micheli, Eduardo F. Fernández, Greg P. Smestad, et al, "A unique global investigation on the spectral effects of soiling losses of PV glass substrates: preliminary results, ieee-pvsc.org/PVSC44/

Experimental procedure

- Seven 4 cm x 4 cm x 3 mm-thick low iron glass coupons shipped to each location.
- Coupon 1 to 6 installed outdoors at zero tilt angle for eight weeks.
- Coupon 0 kept in a dust free container and used to calibrate each spectrometer.
- Weekly transmission measurements for coupons 1, 2, 3.
- Daily weather and particulate matter (PM) concentration recorded.
- A dry cleaning is performed by using a microfiber cleaning cloth.
  - Coupon 1 cleaned every week, Coupon 2 every four weeks.



Experimental procedure

Figure 1. One of the coupons.

Figure 2. Supporting structure.

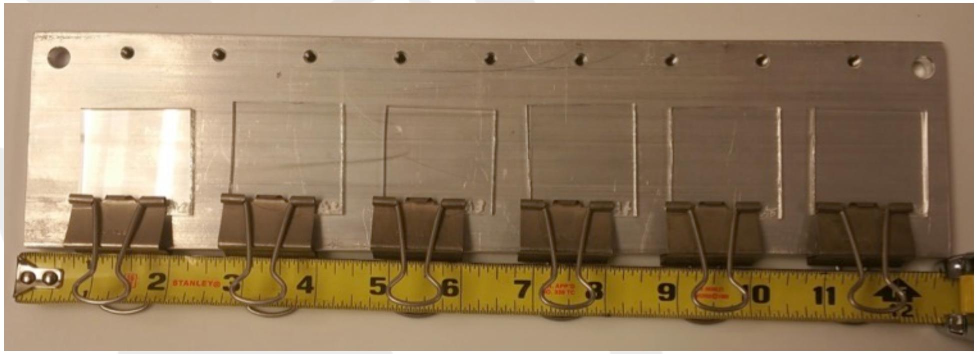
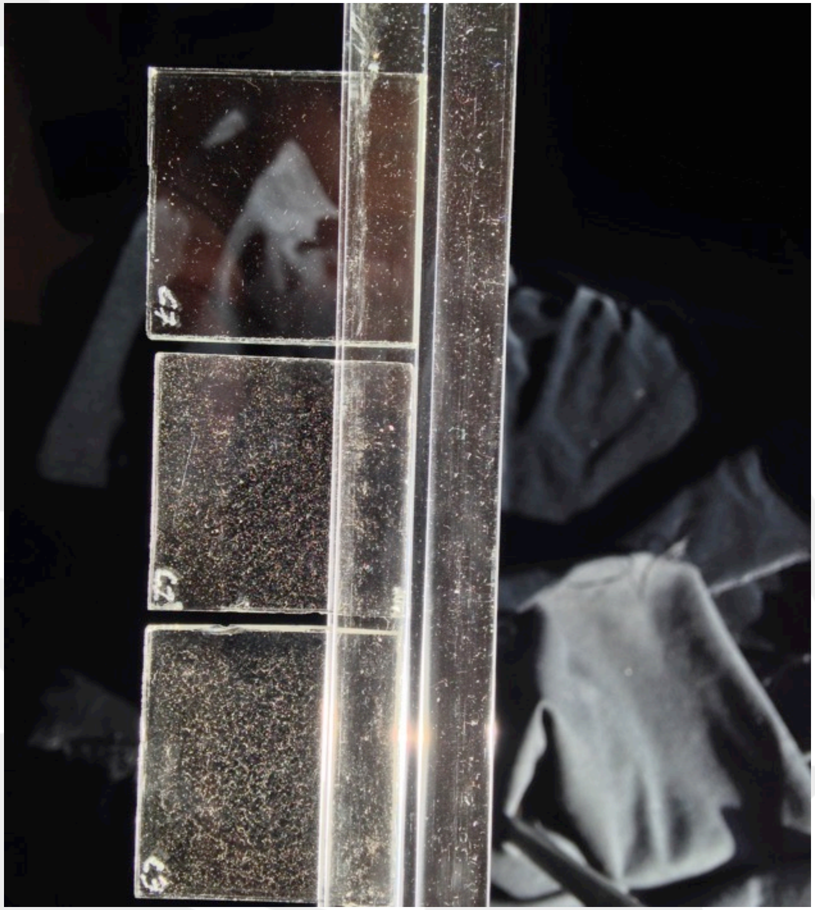
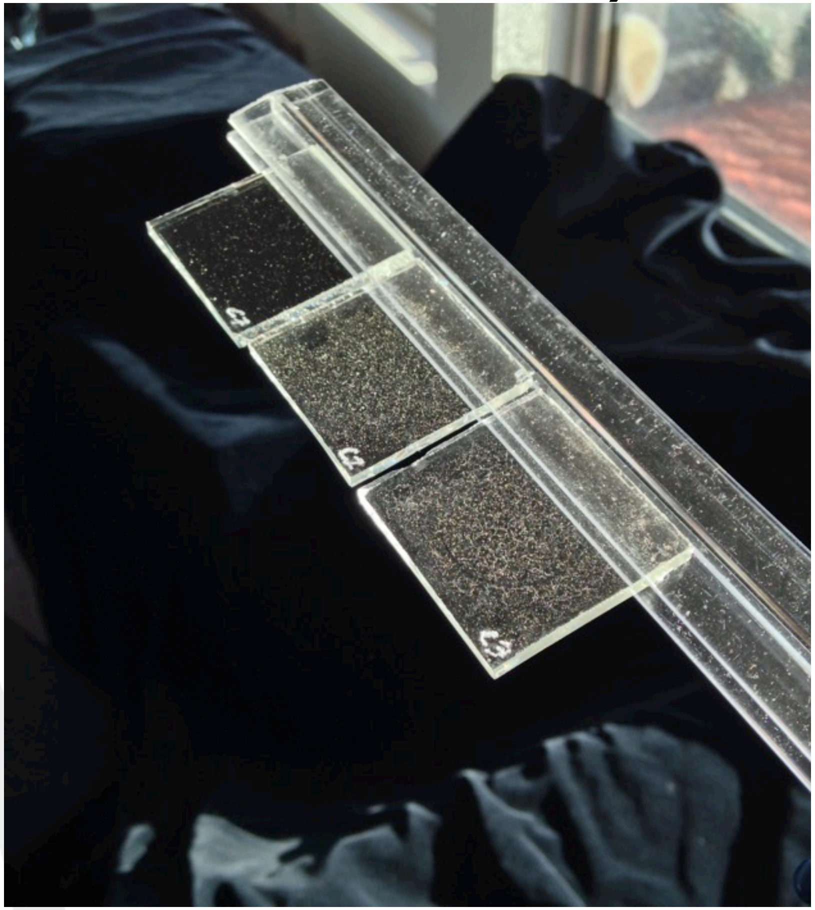


Figure 3. Coupons mounted on the support structure.

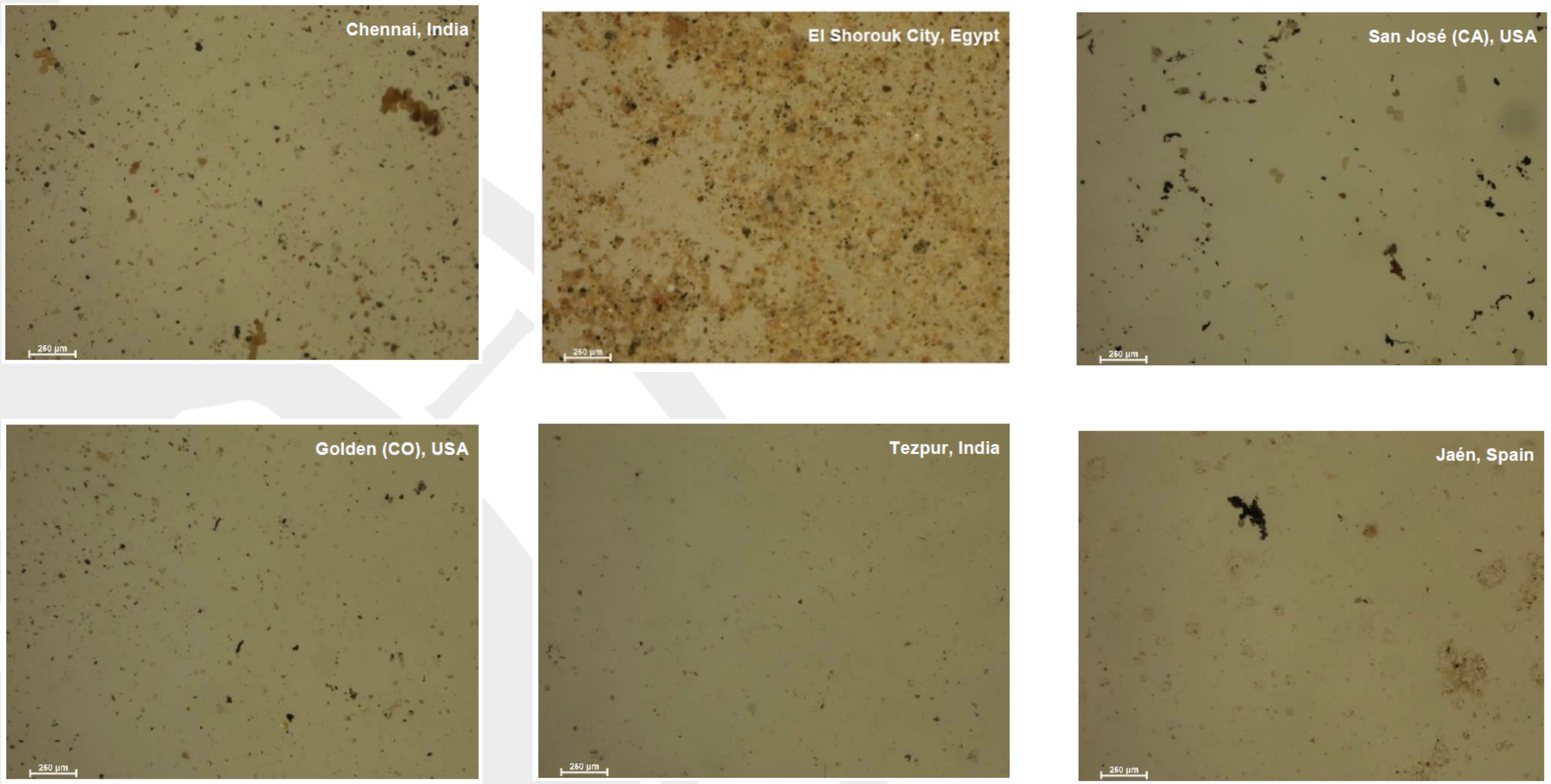
After 8 weeks (San José, CA)





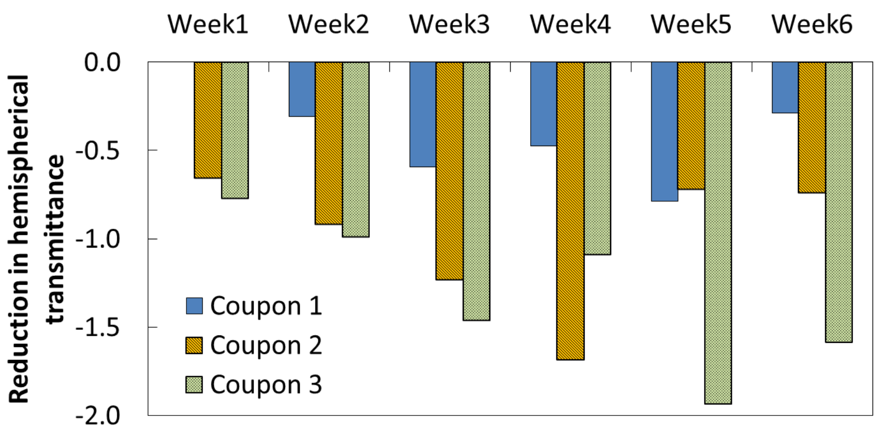
San José, CA (USA), coupon C1, C2, C3. Afternoon sunlight is incident from the right side.

First results: *Coupon 3 (two months of outdoor exposure)*

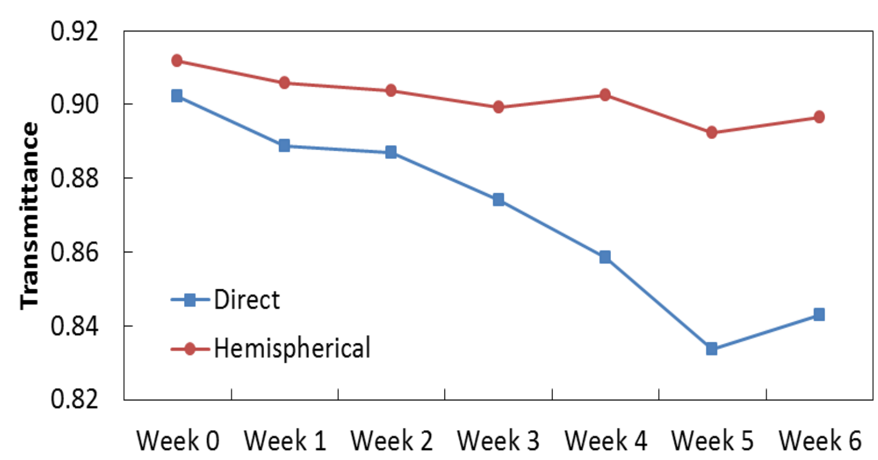


Microscope pictures of six coupons at the end of the data collection. Pictures have been taken using a Nikon SMZ 1500 stereomicroscope at a magnitude of 5×: the scale bar on the bottom left represents a length of 250 μm.

First results

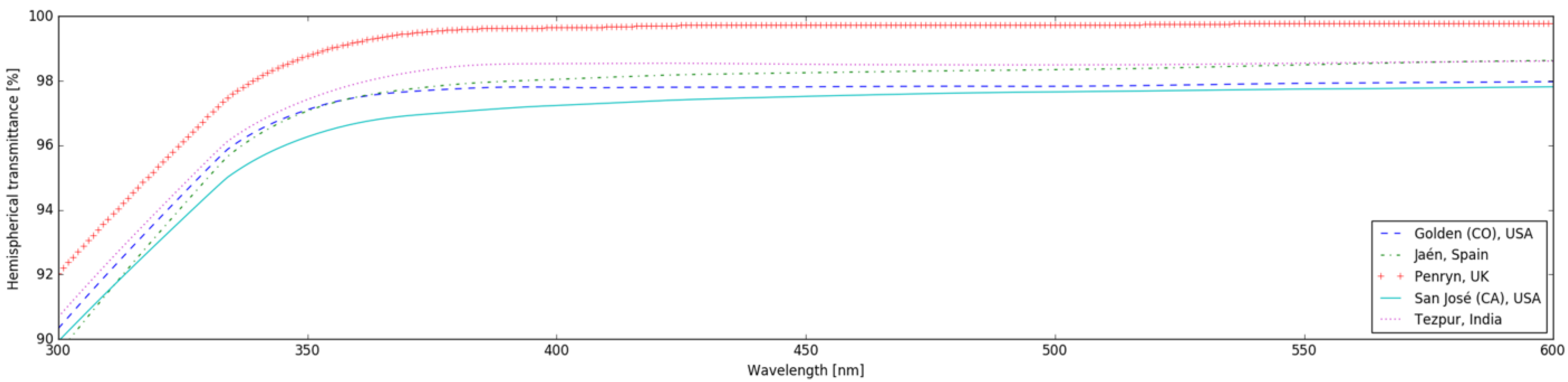


Progressive absolute drop in hemispherical transmittance, compared to the initial conditions, registered in Golden, CO. Transmittance is obtained by averaging the data recorded between 200 and 1100 nm, with a 1 nm step.



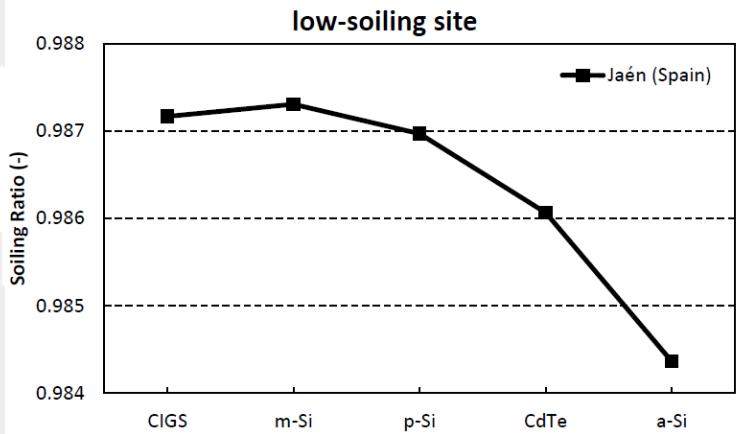
Direct and hemispherical transmittance of coupon 3 in Golden. Wavelengths between 500 and 1100 nm have been averaged.

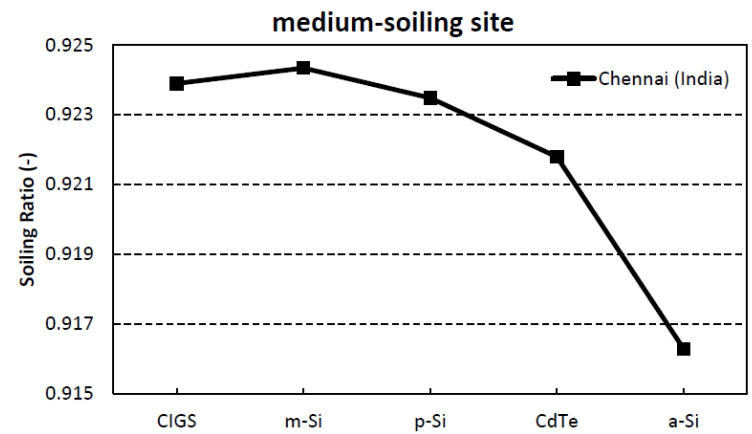
First results: *Coupon 3 (two months of outdoor exposure)*

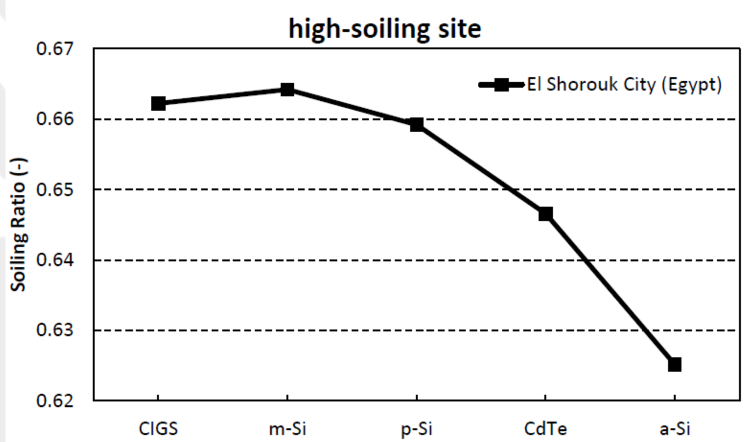


Hemispherical transmittance in the visible and NIR range of coupon 3 for five low soiling sites, referenced to the transmittance of coupon 0. The spectra were measured using a PerkinElmer Lambda 1050 UV/Vis spectrophotometer with a 150 mm integrating sphere at NREL and processed using a local regression technique to remove noise.

Results: *Soiling Ratio for the AM1.5G reference spectrum*







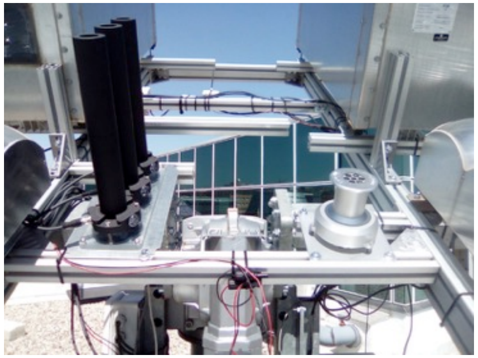
$$Soiling\ Ratio\ (-) = \frac{\int_{\lambda 1}^{\lambda 2} E_G(\lambda)\tau_{soiling}(\lambda)SR(\lambda)d\lambda}{\int_{\lambda 1}^{\lambda 2} E_G(\lambda)SR(\lambda)d\lambda}$$

a) The impact of soiling is higher on materials with high energy gap
b) The difference is higher as the soiling losses increase

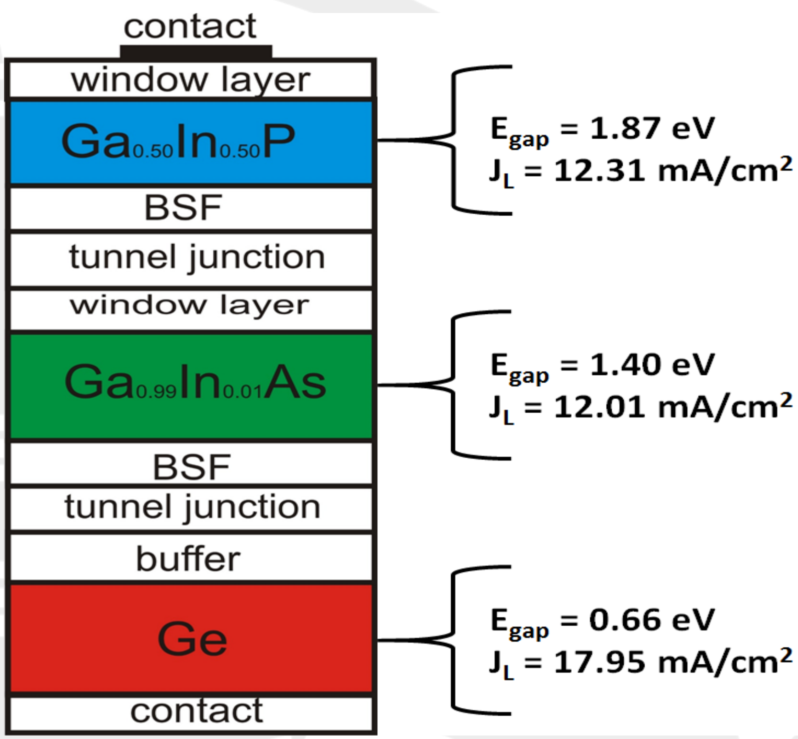
Fernández, E. F. et al.. "Waveband analysis for understanding the soiling impact on PV systems", International PV Soiling Workshop, DEWA and NREL, 09/2017, Dubai.

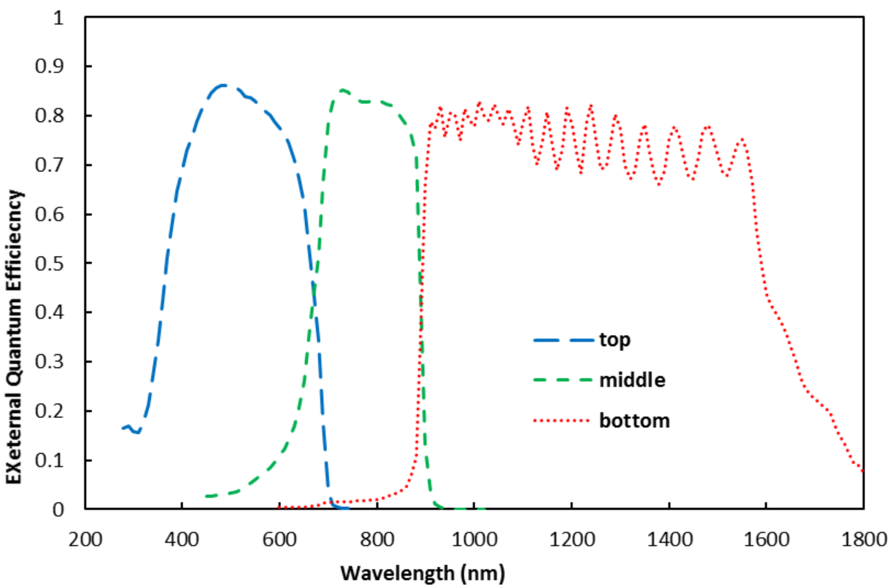
Impact on multi-junction CPV systems

- A one-year experiment was conducted at the University of Jaén (January-December 2017)
- Six 4 cm × 4 cm coupons (i.e. 3 made up of glass and 3 of PMMA) were placed in outdoors
- A Lambda 950 spectrophotometer were used to measure the Direct Transmittance
- Isotype solar cells and a solar spectral irradiance meter SolarSIM-D2 was used to characterize the incident spectrum.
- Rain, PM10 and other parameters were recorded, e.g. irradiances, humidity, temperature, etc.



Impact on MJ CPV systems





Impact on MJ CPV systems: Metrics

Impact on current-balance

$$\mathrm{SMR}atio(-) = {SMR_{soiled}}\big/{SMR_{clean}}$$

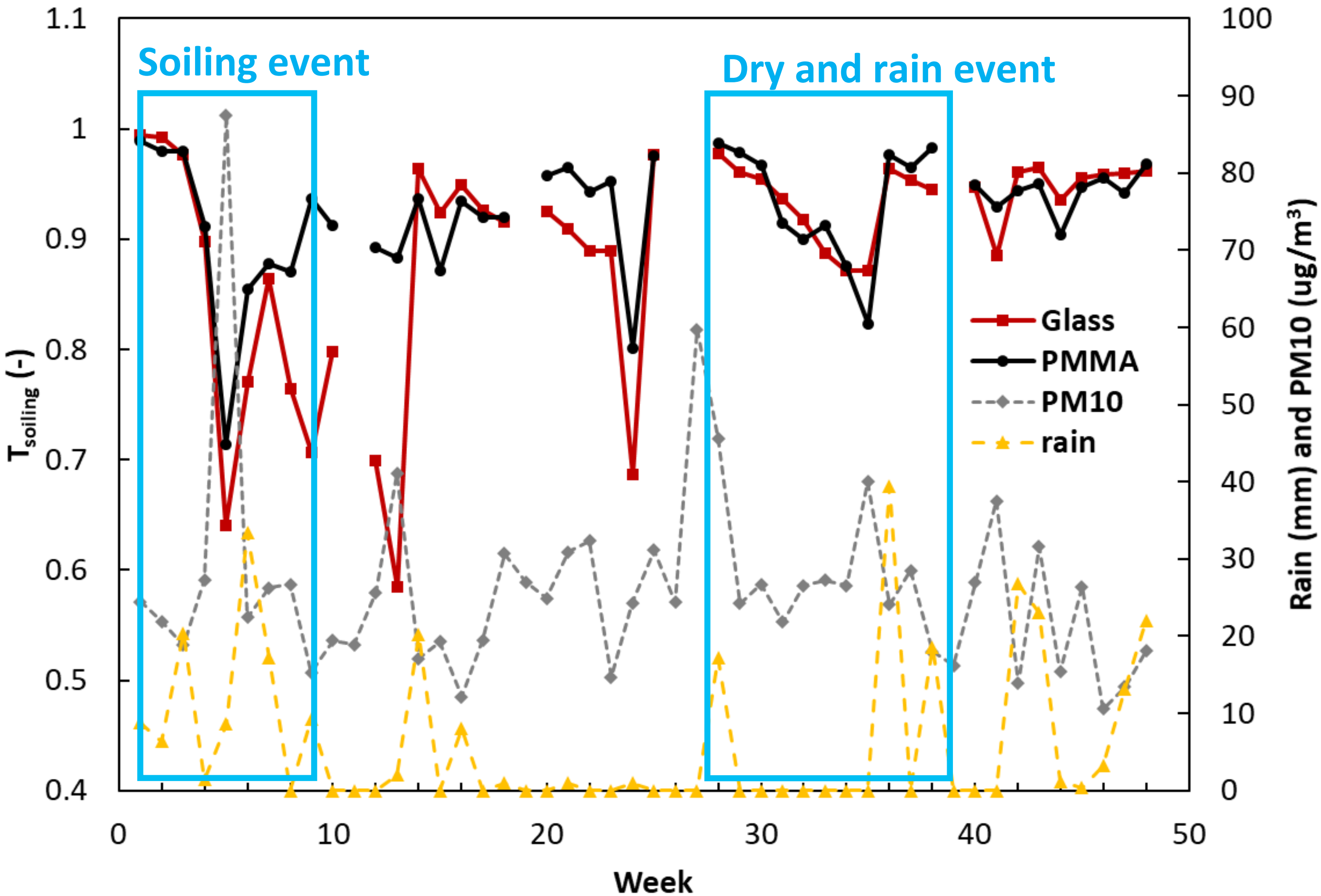
Soiling spectral losses (soiling spectral gains)

SSG $(-) = SG/SBG$

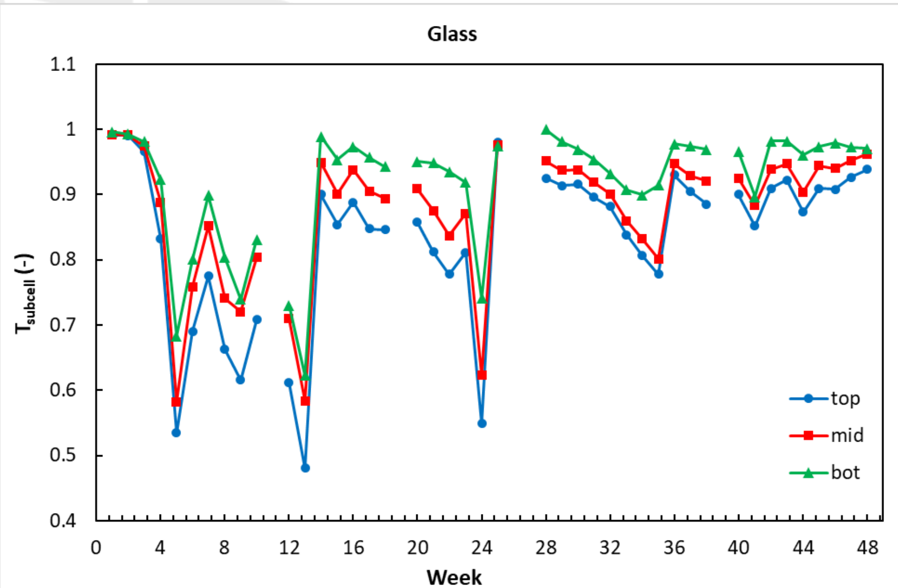
$$Soiling\ Gains\ (-) = SG\ (-) = Soiling\ Ratio\ (-) = \frac{min\left(\int_{\lambda 1}^{\lambda 2} E_b(\lambda)\tau_{soiling}(\lambda)SR(\lambda)_i d\lambda\right)}{min\left(\int_{\lambda 1}^{\lambda 2} E_b(\lambda)SR(\lambda)_i d\lambda\right)}$$

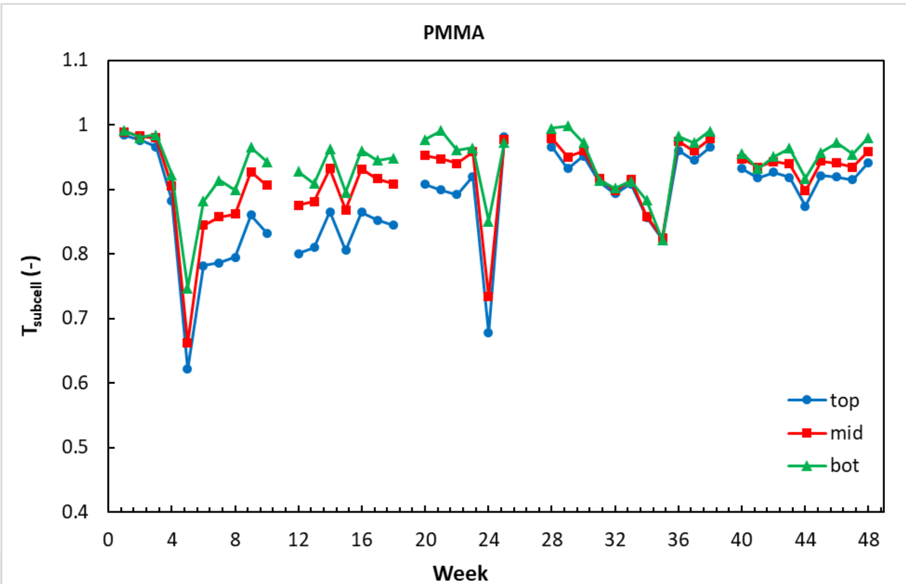
$$Soiling\ Broadband\ Gains\ (-) = SBG\ (-) = \frac{\int_{\lambda min}^{\lambda max} E_b(\lambda)\tau_{soiling}(\lambda)d\lambda}{\int_{\lambda min}^{\lambda max} E_b(\lambda)d\lambda}$$

Broadband transmittance: C3



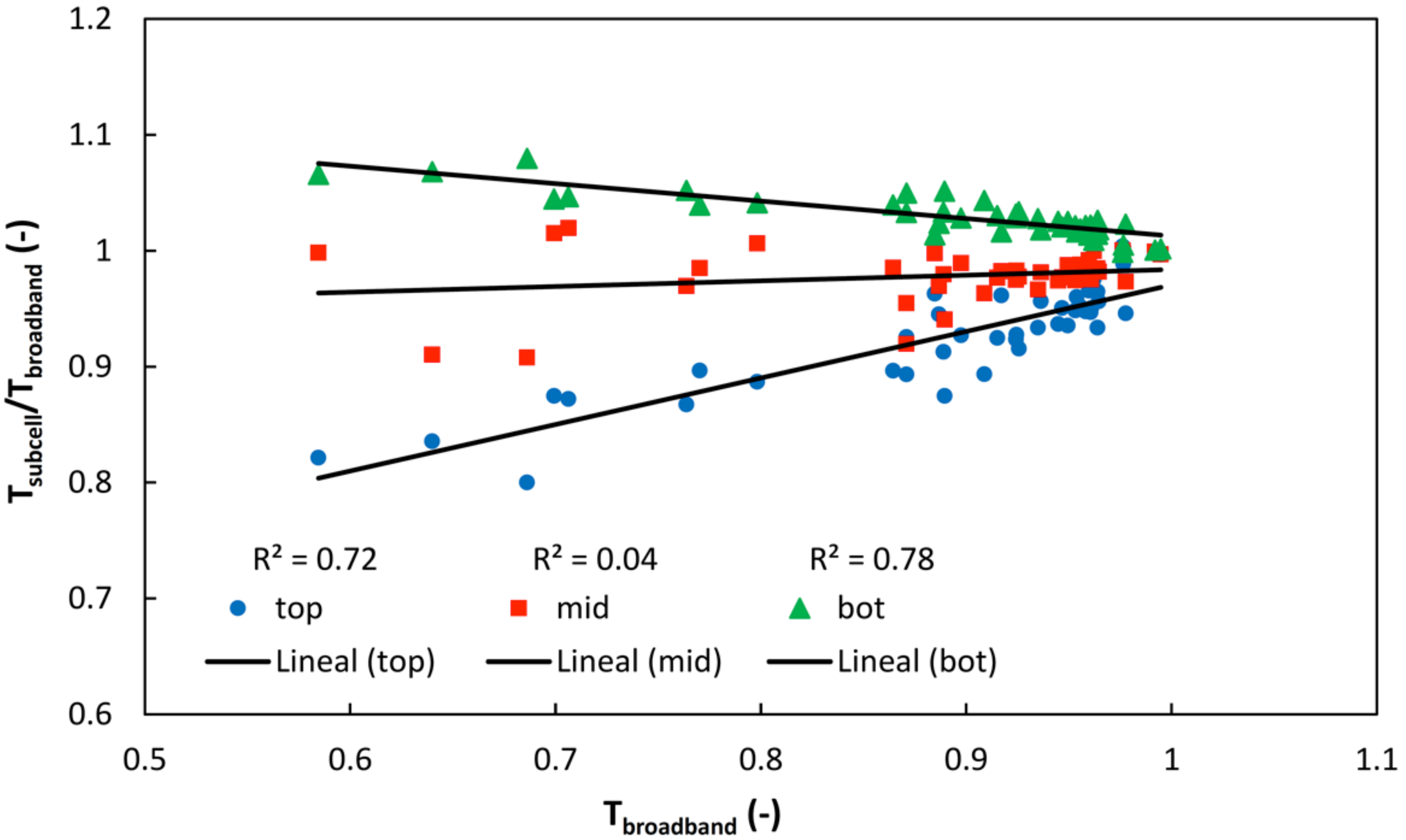
Spectral transmittance: C3



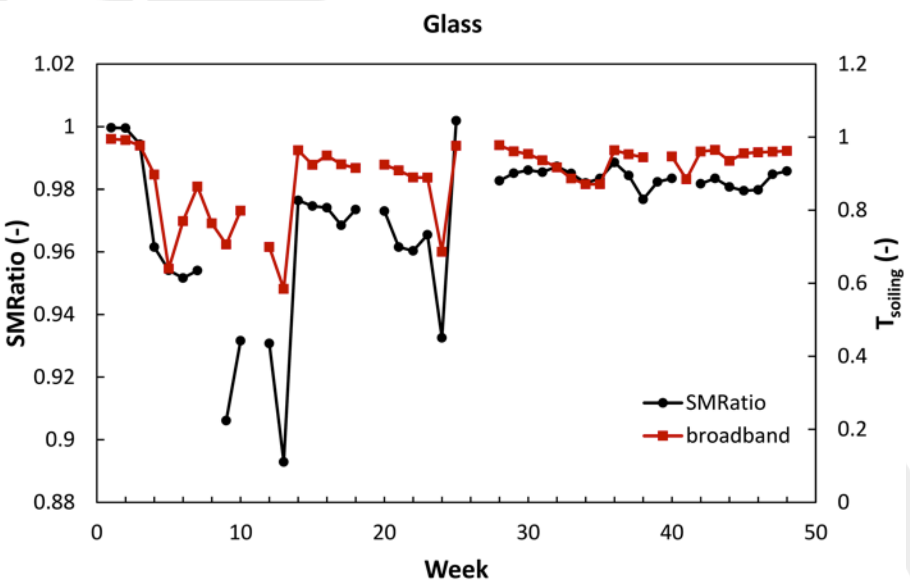


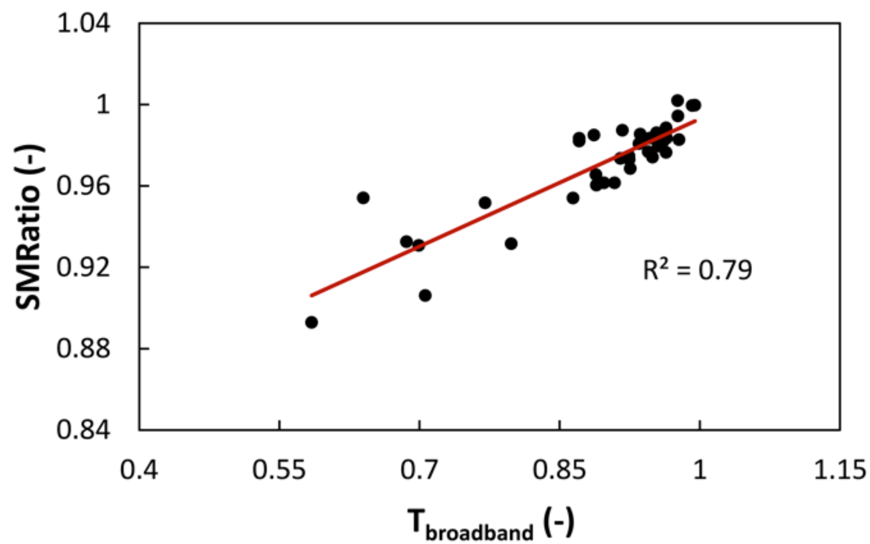
a) Soiling average loses are ≈3%-4% higher on the top junction than in the middle junction of a GaInP/GaInAs/Ge 3J cell.
b) Glass shows average losses ≈ 3%-5% higher than PMMA for all the subcells of a GaInP/GaInAs/Ge 3J cell.

Spectral transmittance: C3



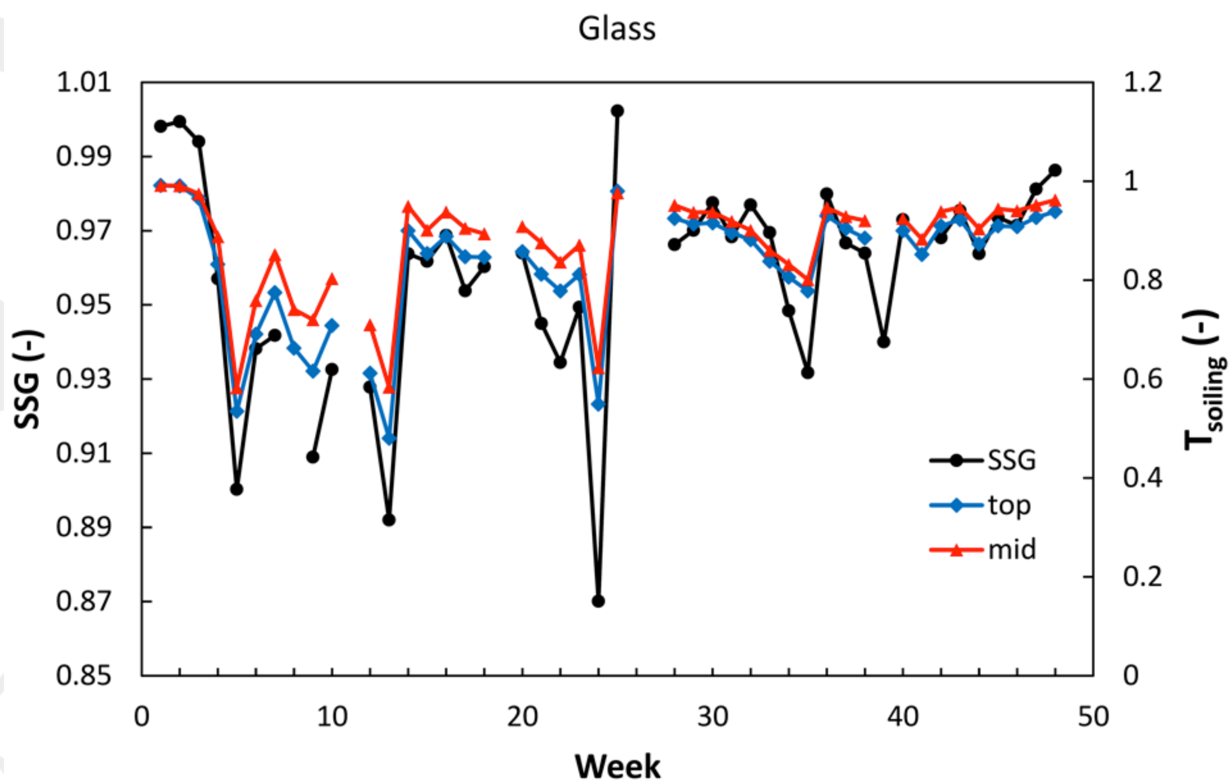
Impact: current-balance (SMRatio) C3





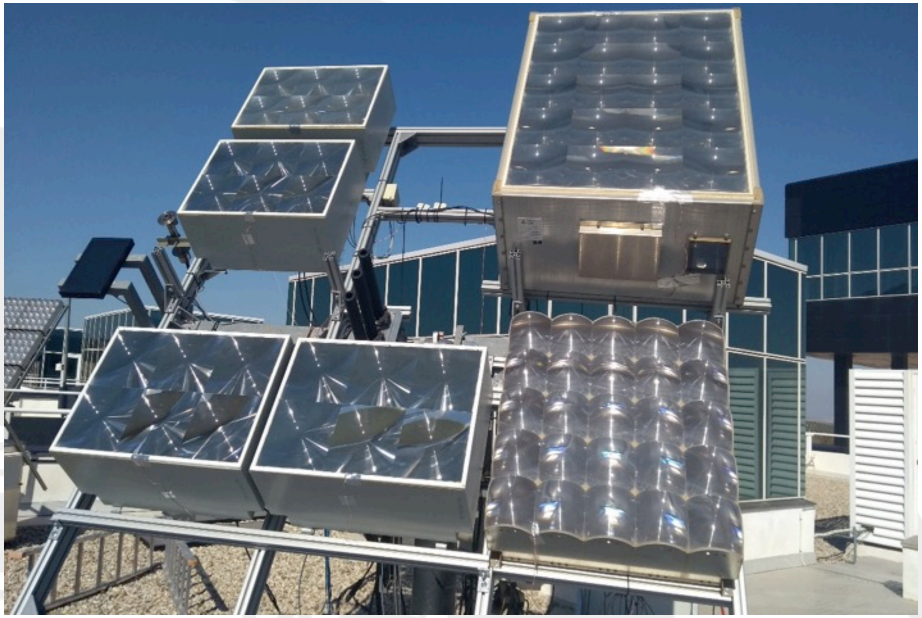
a) Soiling reduces the current of the top junction within 0%-15% respect to the middle junction.
b) The effect on the current balance increases as the transmittance of soiling decreases.

Impact: soiling spectral gains (SSG) C3



Soiling produces additional spectral losses within 0%-15% depending on the amount of soiling and the spectral content of the sunlight.

Are coupons representative of a CPV module?



Preliminary conclusions

- Direct transmission is more affected than hemispherical.
- Soiling produces a higher attenuation at shorter wavelengths, and therefore, a red-shift of the spectral irradiance.
- Soiling reduces the current of the top junction within 0%-15% respect to the middle junction.
- Soiling produces average losses ≈ 3%-5% higher in Glass than in PMMA
- Soiling produces additional spectral losses within 0%-15% due to its impact on the current balance.

THANK YOU FOR YOUR ATTENTION!

Universidad de Jaén

CEAEMA
CENTRO DE ESTUDIOS AVANZADOS EN
ENERGÍA Y MEDIO AMBIENTE

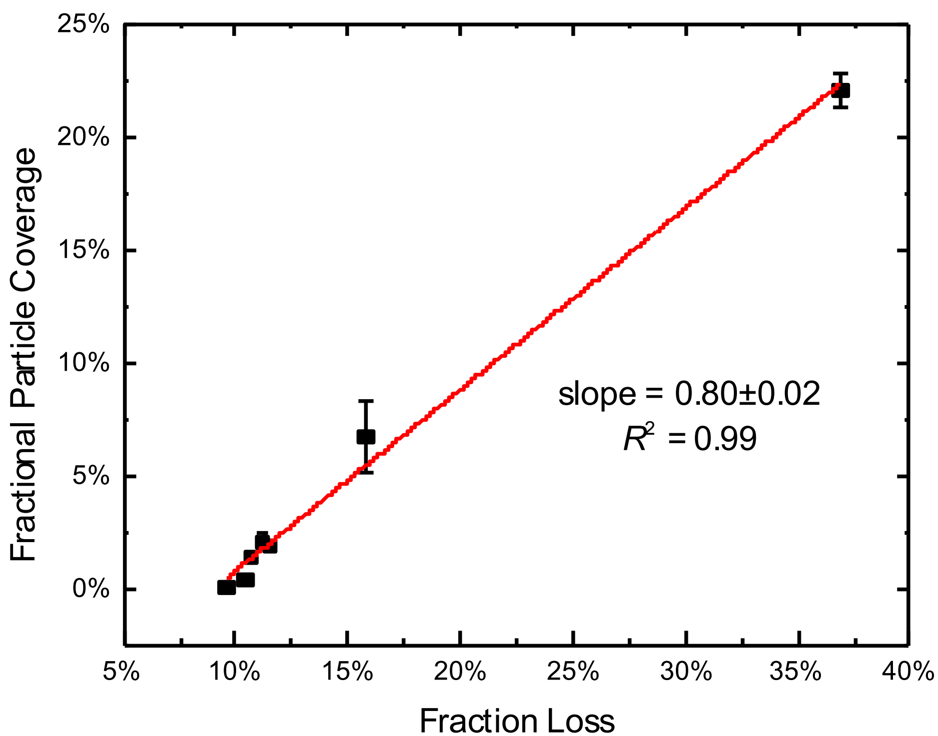
Dr. Eduardo F. Fernández
fenandez@ujaen.es

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
SECRETARÍA DE ESTADO DE INVESTIGACIÓN, DESARROLLO E INNOVACIÓN

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

HORIZON 2020

First results: *Coupon 3 (two months of outdoor exposure)*



Smestad, G. Micheli, L. Germer, T. A. Fernández, E. F., Optical Characterization of PV Glass Coupons and PV Modules Related to Soiling Losses, Atlas/NIST Workshop on PV Materials Durability (2017)